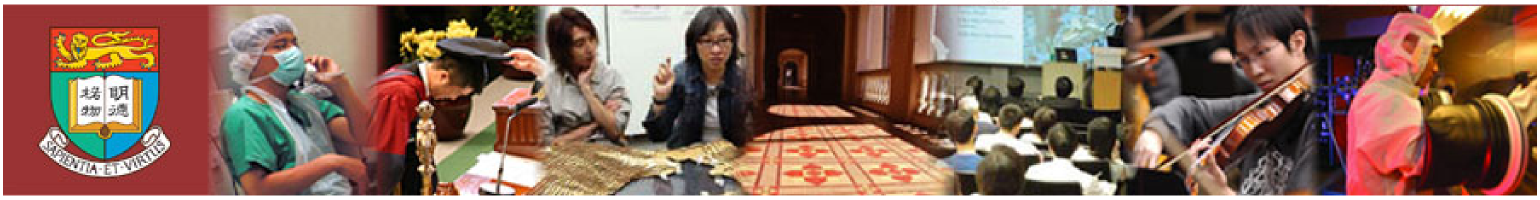

Title	Multiband inverted-f antenna with independent bands for small and slim cellular mobile handsets
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Multiband Inverted-F Antenna With Independent Bands for Small and Slim Cellular Mobile Handsets

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***Abstract*—The design of a small ultra-thin printed inverted-F antenna (PIFA) with independent control on the resonant frequency bands is proposed. The antenna consists of a slotted radiator supported by shorting walls and a small ground plane. The structure is designed and optimized to operate at 2.09, 3.74 and 5 GHz with achievable bandwidths of 11%, 8.84% and 10%, respectively. These three bands cover the existing wireless communication frequency bands from 1.5–6.8 GHz. Each of the three bands can be controlled independently without affecting the other two bands. The 2.09 GHz band can be controlled to operate between 1.5–2.09 GHz (33.33%), the 3.74 GHz band can be controlled over the range of 3.57–4.18 GHz (15.76%) and the 5 GHz band can be controlled to cover the band from 5.00–6.80 GHz (30.50%). Results of intensive investigations using computer simulations and measurements show that the ground plane and the feed locations of the antenna have marginal effects on the performance of the antenna. The effects of the user's hand and mobile phone housing on the return loss, radiation patterns, gains and efficiency are characterized. The measured peak gains of the prototype antenna at 2.09, 3.74 and 5 GHz are 2.05, 2.32 and 3.47 dBi, respectively. The measured radiation efficiencies for the corresponding three bands are 70.12, 60.29 and 66.24% respectively.**

***Index Terms*—Antenna for mobile phone, independent control, printed inverted-F antenna (PIFA), PIFA ground plane, small PIFA, the effect of user's hand, thin PIFA.**

I. INTRODUCTION

PLANAR Inverted-F Antennas are widely used in a variety of communication systems especially in mobile phone handsets due to low profile, light weight, easy integration and manufacturability [1]–[3]. In recent years, there have been a number of PIFA designs with different configurations to achieve single and multiple operations by using different shapes of slots [2]–[11]. Truncated corner technique [12], meandered strips [13] and meandered shapes [14], [15] have been used to create multiple band operations. Branch line slit has been used to achieve dual-band operations [16]. Broadband multi-resonant antennas utilizing capacitive coupling between multiple conductive plates was claimed in a patent [17]. These antennas are generally designed to cover one or more wireless communications bands such as the Global System for Mobile Communications (GSM900 and 800), Personal Communication System (PCS 1800 and 1900), Digital Communication Systems (DCS), Global Position System (GPS), Universal Mobile Telecommunications System (UMTS), Wireless Local Area Networks (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX), etc.

The ground plane of a PIFA can play an important role to enhance the performance of the antenna [18]. For example, for low frequency operation such as for the GSM 900/800 bands, the ground plane has to be used as a radiating part. However, if the ground plane also acts as a radiating part, the effect of the user's hand is likely to degrade the antenna performance when the antenna is fitted inside the mobile phone. This causes several practical engineering problems [19]–[22]. In some designs, the location of the antenna on the substrate is also an important factor to be considered as it can enhance the bandwidth of the antenna by few more percentages [23].

Some work has been done to achieve frequency independent control for a small-size and thin antenna. For example in [24], a Planer Inverted-F Antenna (PIFA) was thoroughly studied to control three resonant frequencies for GSM/DCS/DMB with an overall size of $105 \times 30 \times 9\ \mathrm{mm}^3$. However, the structure of the antenna could not provide a wide-independent control for the three resonant frequency bands and the large ground plane also affected the frequency bands. In [25], a switchable design for dual bands at (1.9 GHz, 5.2 GHz) and (1.9 GHz, 3.5 GHz) was presented with some tuning capability for a reconfigurable system. In [26], a double U-Slot patch antenna was proposed to independently control three WiMAX bands. However, the control ranges of the three bands were limited to only few percentages. In the patent reported in [27], [36], a multi-frequency band antenna, capable of tuning the low-band portion to a low frequency band and the first high-band portion to a first high frequency band, was introduced for use in mobile handsets applications.

In this paper, the design of a relatively small and ultra-thin PIFA that can support three frequency bands at 2.09 GHz, 3.74 GHz and 5 GHz with achievable bandwidths of 10%, 8.8% and 11%, respectively is proposed and presented. The effects of different ground plane dimensions, locations of the antenna on the substrate and physical heights of the antenna from the ground plane are studied. The three bands can be independently designed over a wide range and also re-designed to any other bands between 1.5 GHz to 6.8 GHz. The proposed antenna satisfies the

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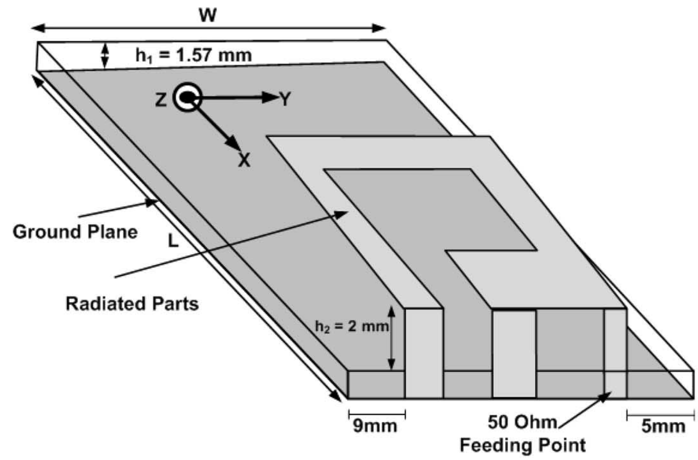
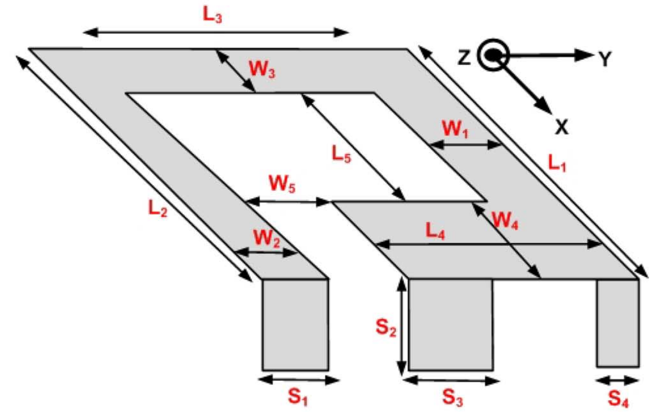


(a)



(b)

Fig. 1. The layout of the proposed antenna (a) 3D view and (b) detailed dimensions.

TABLE I
DETAILED DIMENSIONS OF THE PROPOSED ANTENNA (IN MILLIMETER)

Parameter	W	W_1	W_2	W_3	W_4	W_5
Dimension	40	6	2	2	11.6	4
Parameter	L	L_1	L_2	L_3	L_4	L_5
Dimension	40	25.6	25.6	20	20	12
Parameter	S_1	S_2	S_3	S_4	Ground Plane	
Dimension	2	3.57	4	3	40 x 40	

return loss, bandwidth, gain and efficiency requirements for applications within the frequency range from 1.5 GHz to 6.8 GHz. The measured reflection coefficient, radiation pattern, gain and radiation efficiency are characterized. The effects of a user's hand model and the mobile phone housing model on the return loss, gain, radiation pattern and efficiency are also studied.

II. DESIGN OF SMALL AND THIN PIFA

A. Antenna Configuration and (S_{11}) Measurements

Fig. 1(a) shows the structure of the proposed antenna with detailed dimensions given in Fig. 1(b) and Table I. The proposed antenna consists of a main radiator with an irregular shape, a rectangular slot, shorting walls, and a ground plane. The material used is FR-4 substrate with a dielectric constant of 4.4, a loss tangent of 0.02 and a substrate height of 1.57 mm. The proposed antenna has a very small size and is physically thin. The total volume of the radiator with feed point is $25.6 \times 26 \times 3.57\ \mathrm{mm}^3$, while the overall volume of the antenna including the ground plan is $40 \times 40 \times 3.57\ \mathrm{mm}^3$. The EM software, High Frequency Structure Simulator (HFSS) V.11.4 package, is used for full wave analysis of the antenna and material losses is taken into account in the simulation studies.

To validate the simulated results, the proposed antenna is also fabricated on a FR-4 substrate with the same characteristics used in simulation. The thickness of the copper used in the prototype is 0.15 mm. The simulated and measured reflection coefficient (S_{11}) of the proposed antenna is presented in Fig. 2(a) and the prototype is shown in Fig. 2(b). It can be seen that the simulated and measured results are in good agreements. The little discrepancies might be due to many factors such as the soldering proficiency and accuracy of cutting the edges of the copper. The results in Fig. 2(a) show three distinct bands are generated at 2.09 GHz, 3.74 GHz and 5 GHz. The corresponding bandwidths defined by -6 dB for the three bands are 11% (1.978–2.2 GHz) for the 2.09 GHz band, 8.84% (3.571–3.9 GHz) for the 3.74 GHz band and 10% (4.887–5.391 GHz) for the 5 GHz band. These bandwidths satisfy the requirements for most of the wireless applications. The antenna achieves a wider bandwidth, smaller ground plane size and thinner structure than the designs reported in [24] and [25].

B. Radiation Mechanism and Current Distributions

Further understanding of the antenna behaviour can be observed from the current distribution plots shown in Fig. 3(a)–(c). These current distribution plots can be used to identify the electrical lengths for the first, second and third resonant frequencies, f_1, f_2 and f_3, at 2.09 GHz, 3.74 GHz and 5 GHz, respectively. It can be seen in Fig. 3(a) that there are two major current paths on the radiator generating the 2.09 GHz band. The first current path is along L_1 and W_1 whereas the second current path is along L_2 and W_2 of Fig. 1(b). Both paths have an electrical length of about a quarter wavelength at 2.09 GHz. At 3.74 GHz, Fig. 3(b) shows that there is only one major current path concentrated along L_3 and W_3 on the radiator. This path has an electrical

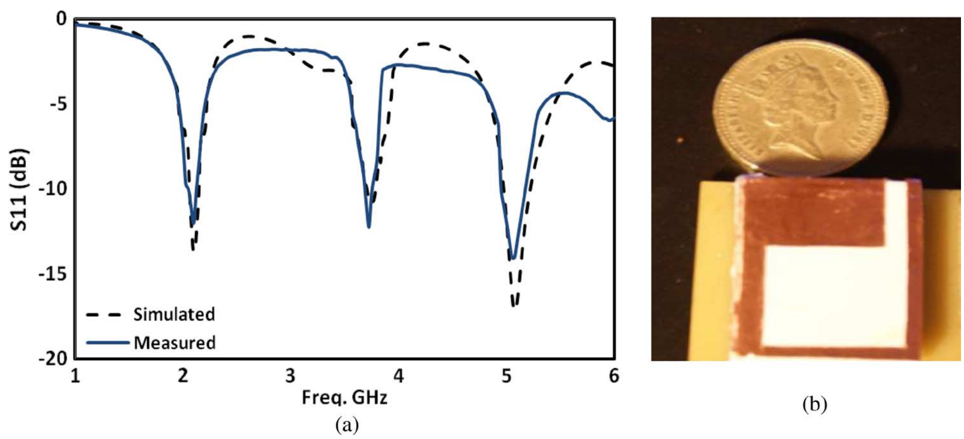


Fig. 2. (a) Simulated and measured S_{11} for the proposed antenna (b) prototype antenna.

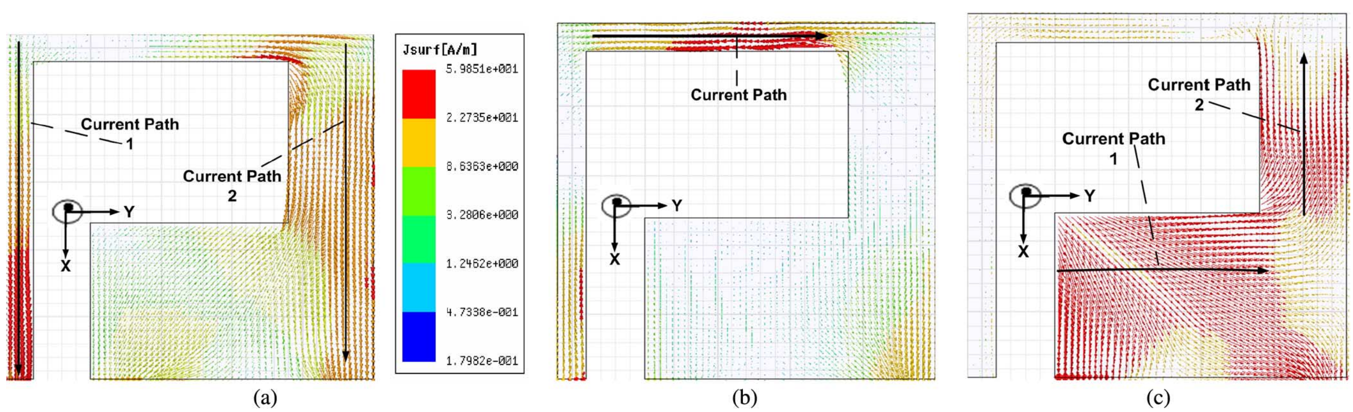


Fig. 3. Currents distribution for the proposed antenna at (a) 2.09 GHz, (b) 3.74 GHz, and (c) 5 GHz.

length of about a quarter wavelength at 3.74 GHz. In Fig. 3(c), there are two major current paths on the radiator. The first path is formed around W_1 and $(L_1 - W_4)$ whereas the second path is formed around L_4 and W_4. The electrical lengths for both paths are about a quarter wavelength at 5 GHz. Thus by varying these parameters, the current paths for the first, second and third resonances can be independently controlled over a wide range, which is further elaborated in the next section.

C. Parametric Analysis and Independent Control Over a Wide Range

To design an antenna with multiple band operation, it is desirable to have an independent frequency control on two or more separate frequencies. Achieving this option is very challenging. Very often, when one parameter is changed, all the other frequencies are affected [28], [29] and the antenna needs to be completely redesigned for other bands.

The idea proposed in this paper to achieve an independent frequency control on different frequencies of a single antenna is to find out the radiation elements of the antenna responsible for individual bands. From the current distribution discussions in Section II-B, we can identify the key radiation elements by observing the current paths for each resonant frequency, so we can control each band independently. For example, the current path along L_2 and W_2 is for the 2.09 GHz band. Increasing the length of L_2 in the X-direction moves the lower order mode resonance (at 2.09 GHz) toward the lower frequencies as shown in Fig. 4(a) and Table II. The 2.09 GHz band can be controlled over 33.33% between 1.5–2.09 GHz. Similarly, the current path for 3.74 GHz is along L_3 and W_3, so by changing the size of the width of W_3 in the X-direction (without changing the parameters (L_1 and W_1)), the 3.74 GHz band can be tuned to a lower or higher frequency, as shown in Fig. 4(b) and Table II. Here, we can tune the 3.74 GHz band over 15.75% between 3.57–4.188 GHz. For the 5 GHz band, the current path is formed along L_4 and W_4. By varying the length and the width simultaneously, we can tune the 5 GHz band over 30.50% between 5–6.8 GHz without affecting the 2.09 GHz band and the 3.74 GHz bands, as shown in Fig. 4(c) and Table II. It should be noted that the 2.09 GHz and 5 GHz bands have one common current path around L_1 and W_1, so by changing the length or the width of L_1, these two bands can be controlled without affecting the 3.74 GHz band. Since these three bands can be controlled independently over wide frequency ranges (compared with the design reported in [24] and [26]), the antenna can be designed easily for other applications.

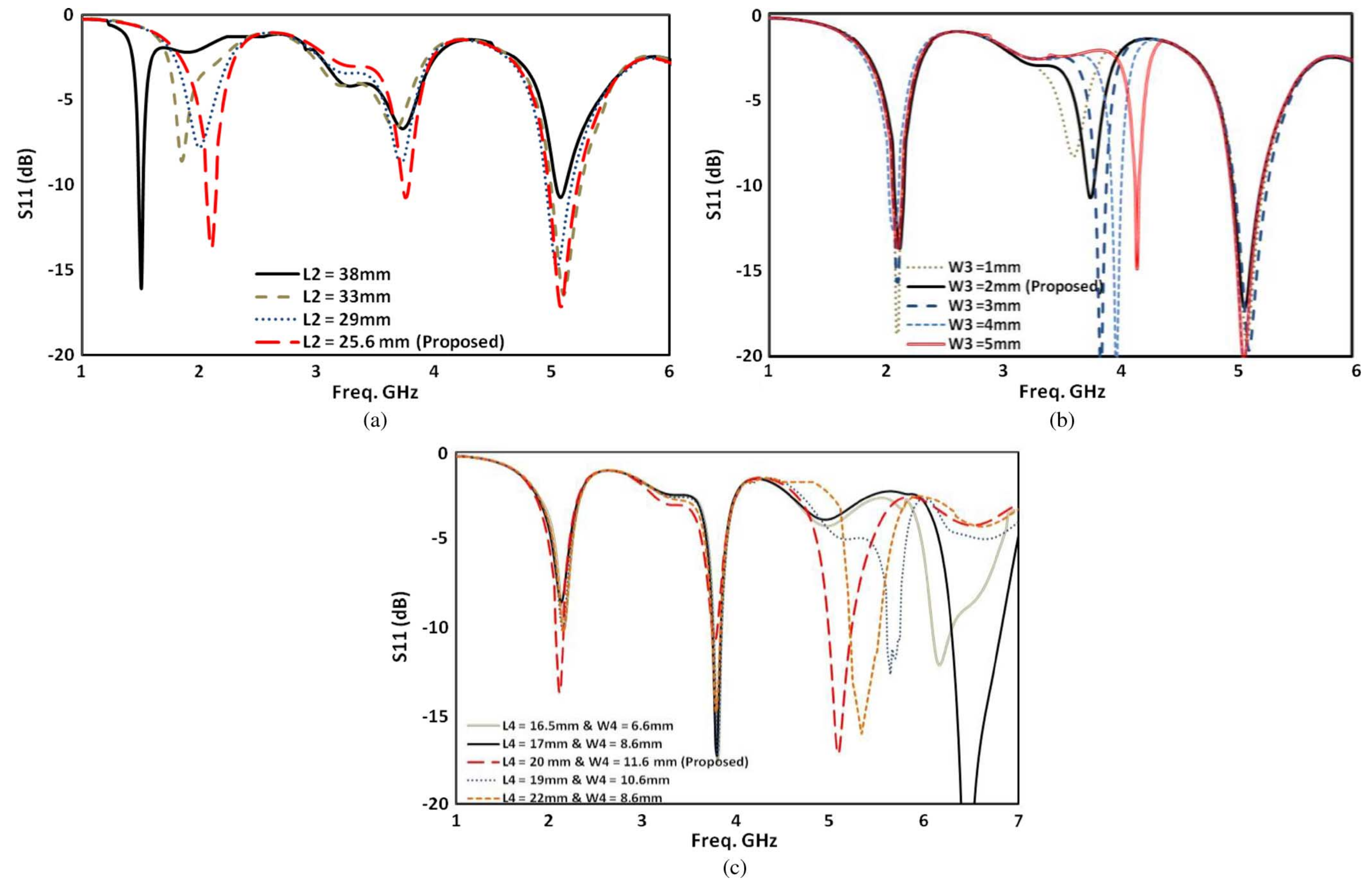


Fig. 4. Parametric studies showing independent control for each band over wide range (a) 2.09 GHz band, (b) 3.74 GHz band, and (c) 5 GHz band.

TABLE II
INDEPENDENT CONTROL RANGE IN THREE BANDS

Frequency Band	2.09 GHz	3.74 GHz	5 GHz
Control Range (MHz)	1500 - 2090	3570 – 4188	5000 - 6800
Control Range (%)	33.33	15.76	30.50

III. SIGNIFICANCE OF SOME PARAMETERS ON ANTENNA PERFORMANCE

The effects of the ground plane size, the antenna location and the height of the PIFA on the performance of the antenna are examined and further elaborated in this section.

A. Ground Plane Effect

The side and geometry of a ground plane in a PIFA are known to affect the antenna performance. In [30], slots were added to the ground plane to significantly improve the bandwidth performance of the antenna. In [24], it was shown that varying the ground plane size would affect S_{11}. An antenna can be designed to couple more energy to the ground plane, making the ground plane a radiating part and resulting in a wider impedance bandwidth. However, this makes the ground plane quite sensitive. Since our proposed antenna is designed for use in the mobile phone systems which require a relatively narrow width, there is no need to use the ground plane to increase the bandwidth. Moreover, there are many advantages of having a less sensitive ground plane. For example, with an insensitive ground plane, the antenna performance will not be affected by other electronic components and circuits nearby. When multiple antennas are integrated together, there will be strong isolation between antennas, allowing easy optimization of antennas positions. The antenna can be used in mobile phones with different ground plane sizes without changing the performance. The user's hand will not affect the matching of the bands and also the radiation efficiency [31]. For these reasons, we should design the antenna to have the ground plane as less sensitive as possible so that the performance mainly depends on the structure alone and not the surrounding elements [19], [22]. For our proposed antenna, results in Fig. 5(a) show that varying the length of the ground plane from 40 $\times$ 40 mm to 40 $\times$ 100 mm does not affect the

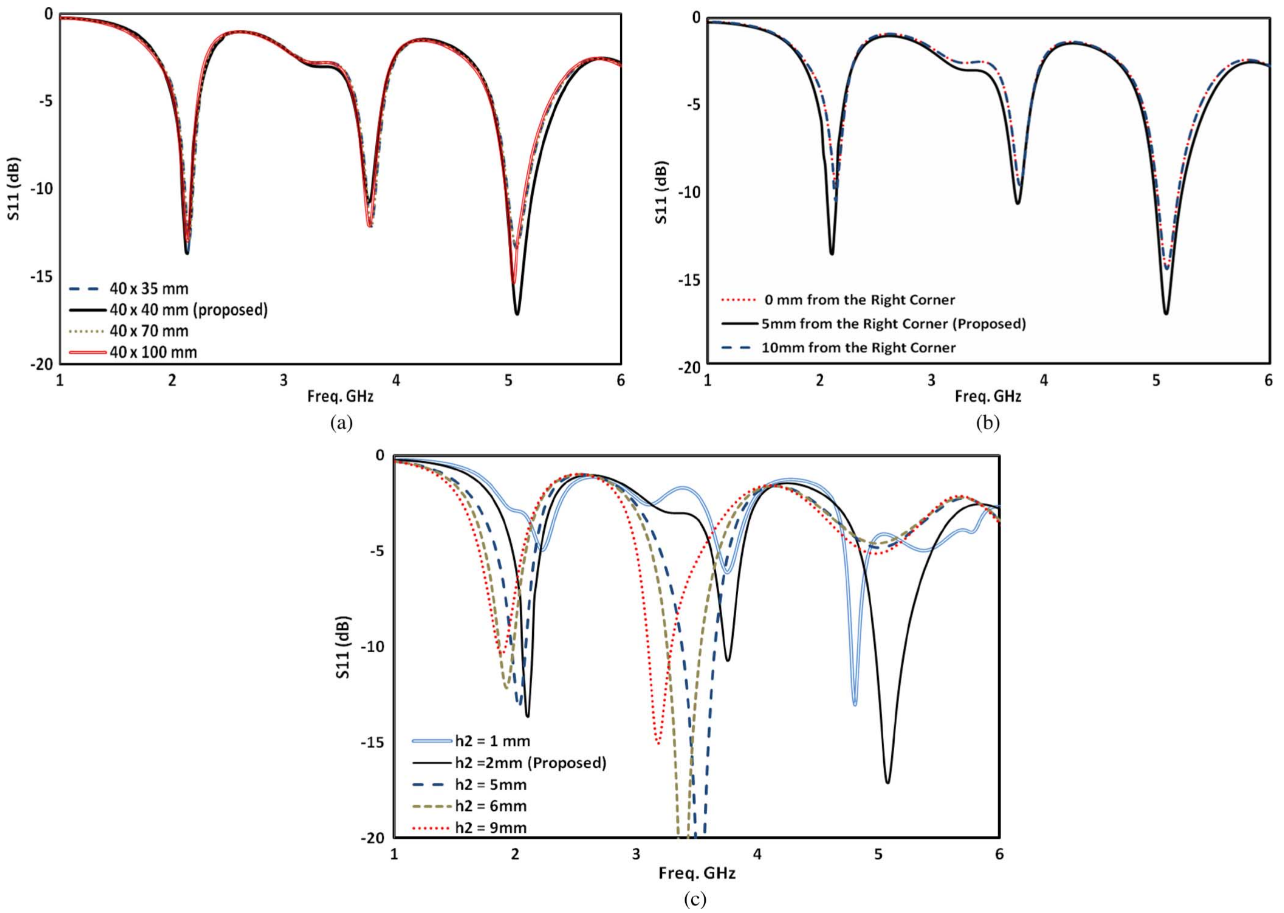


Fig. 5. The effects of (a) ground plane size, (b) antenna location, and (c) physical height of the PIFA on S_{11} performance.

matching or the bandwidth of the antenna, indicating that the ground plane effect is quite small. Similar observation was also reported in [23]. However, this will not be the case if the ground plane is used as part of the radiating part as in [24] and [30].

When the size of the ground plane changes the current distribution on the main radiator and the ground plane for the three bands do not significantly change. Also the gain and the radiation efficiency have been observed when changing the size of the ground plane. No significant changes in the gain and the radiation efficiency have been noticed at the three bands.

B. Antenna Location

The location of the antenna can also affect the performances [23]. However, in our proposed antenna, results in Fig. 5(b) shows that changing the location of the proposed antenna along the substrate does not affect the matching or bandwidth of the bands. More results have also shown that this would not change the gain and the shape of the radiation pattern.

C. Height of the PIFA (h_2)

Fig. 5(c) shows the effects of the height (h_2) of the PIFA above the ground plane on the bandwidth of the antenna. It can be seen that, at a smaller value of $\mathrm{h}_2 = 1\ \mathrm{mm}$, the reflection coefficient is larger at the high frequency band and significantly lower at only 5 dB in the lower frequency band. This is because the radiator was too close to the substrate base to resonate at low frequency. At the heights of $\mathrm{h}_2 = 5$, 6 and 9 mm, the return loss is larger than 10 dB $(\mathrm{S}_{11} < -10\ \mathrm{dB})$ in the low frequency band, but less than 5 dB in the high frequency bands. With $\mathrm{h}_2 = 2\ \mathrm{mm}$, the return losses of the three bands are larger than 10 dB which satisfies many applications. Since the objective of this research is to design a small antenna with a thin structure, we have selected the heights $\mathrm{h}_2 = 2\ \mathrm{mm}$ from the substrate and 3.57 mm from the ground plane for further studies. With these dimensions, the proposed antenna can operate in the UMTS, m-WiMAX and 5 GH WLAN bands with a bandwidth wide enough to cater for these applications. More results have also shown that changing h_2 does not alter the radiation efficiency and gain of the antenna significantly enough to affect the performance, except at 5 GHz for $\mathrm{h}_2 = 9\ \mathrm{mm}$, where the efficiency changes slightly.

IV. Simulation and Measurements

A. Measurements Setup

The antenna is measured using the antenna measurement equipment, StarLab, manufactured by Satimo [31]. Before any measurement is done, calibration is carried out by using the standard antennas provided. For radiation pattern and gain measurements, it is just like other antenna measurement equipment. For power efficiency measurement, the equipment first measures the gain, radiation intensity and reflection coefficient of the antenna and computes the directivity using the radiation

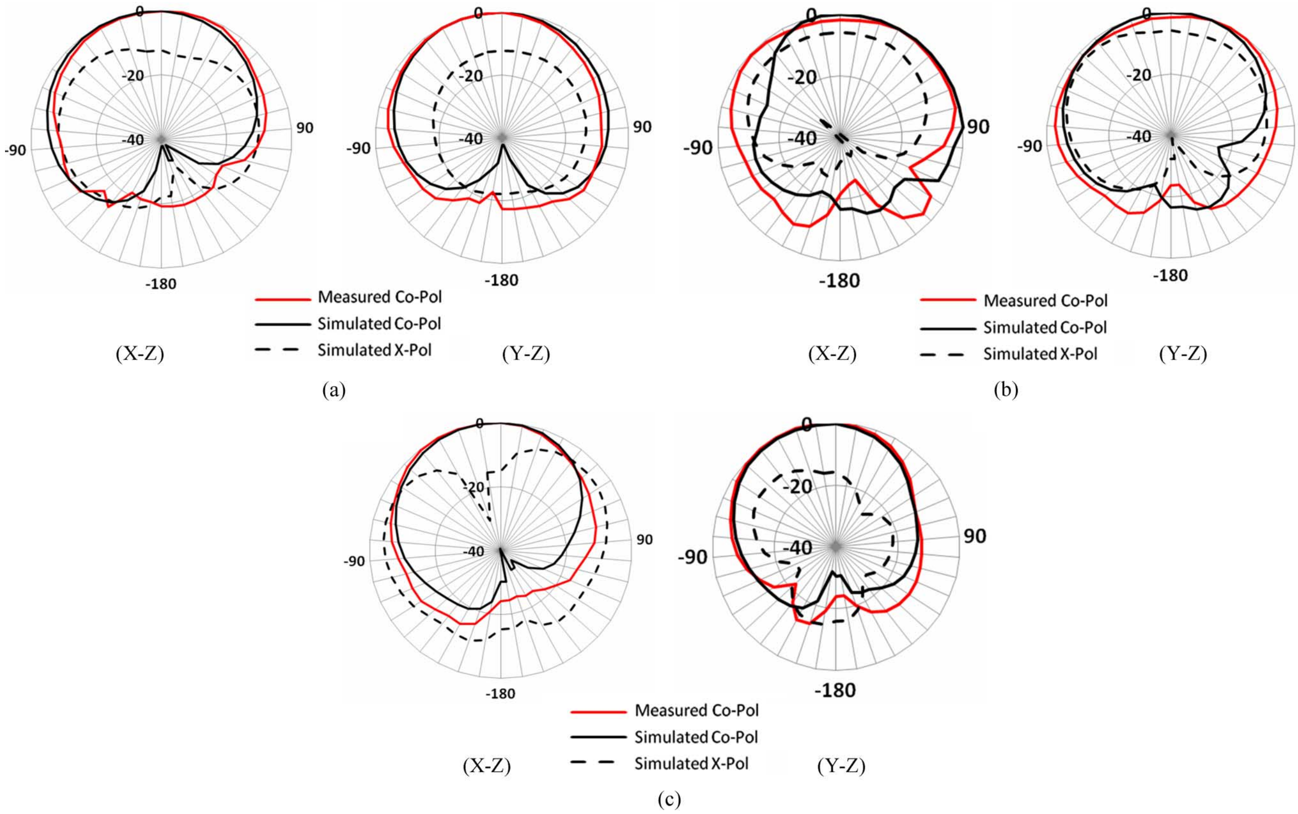


Fig. 6. Simulated and measured Co and X-pol radiation patterns in E and H planes (a) 2.09 GHz, (b) 3.74 GHz, and (c) 5 GHz.

intensity. The efficiency of the antenna is then computed using the equation:

$$Efficiency = \frac{G(\theta,\phi)}{D(\theta,\phi)}\left(1-|\Gamma|^2\right)$$

where Γ is the voltage reflection coefficient, $G(\theta,\phi)$ and $D(\theta,\phi)$ are the gain and directivity, respectively, of the antenna and are functions of spherical coordinate angles θ and ϕ. The directivity is calculated by using the radiation intensity [32].

B. Simulated and Measured Radiation Patterns and Its Relationship With Current Distribution

The simulated and measured radiation patterns for co- and cross- polarizations in the E-plane and H-plane at the frequencies of 2.09, 3.74 and 5 GHz are shown in Fig. 6(b)–(d). It can be observed the radiation patterns are quite stable throughout the UMATS, m-WiMAX and WLAN bands. To relate the X-Y-Z orientation of the antenna in Fig. 1 to the E- and H-planes in Fig. 6, we use the current directions of Fig. 3(a)–(c) on the radiator in the individual frequency bands. Fig. 3(a) shows that the current direction for the first band at 2.09 GHz is in the X-direction, so the E- and H-planes in Fig. 6 are the X-Z and Y-Z planes, respectively, in Fig. 1. The current direction for the second band at 3.74 GHz is in the Y-direction as shown in Fig. 3(b), indicating that the E- and H-planes are the Y-Z and X-Z planes, respectively. Here, a high cross-polarization level is found at 3.74 GHz. This might be due to high current concentration around the feed and the end of L_1, as shown in Fig. 3(b). Finally, the

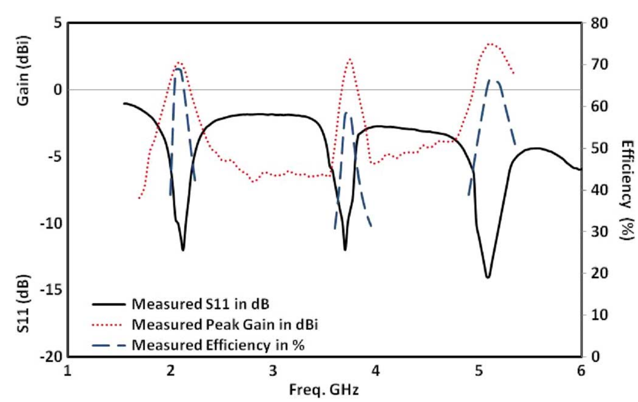


Fig. 7. Measured S_{11}, peak gain and radiation efficiency.

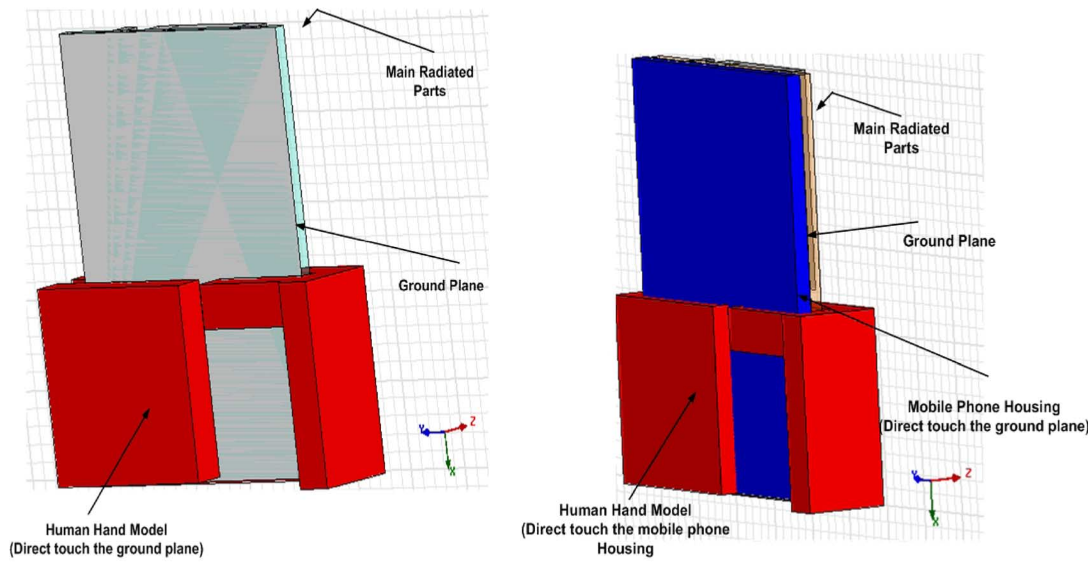
current direction for the 5 GHz band in Fig. 3(c) indicates that the E- and H-planes are the Y-Z and X-Z planes, respectively. To conclude these, at 3.74 GHz and 5 GHz, the currents have the same direction and their E-planes are the Y-Z plane, whereas at 2.09 GHz, the current has a different direction and the E-plane is the X-Z plane.

C. Measured Gain and Radiation Efficiency

Simulations and measurements on the peak gain and radiation efficiency of the antenna have been carried out. Results have shown that, in the 2.09 GHz, 3.74 GHz and 5 GHz bands, the simulated peak gains are 2.14 dBi, 2.4 dBi and 5 dBi, respectively, and the corresponding measured peak gains 2.05 dBi,

TABLE III
SIMULATED AND MEASURED GAIN AND EFFICIENCY WITH AND WITHOUT THE MATERIAL LOSSES

Parameters		(f_1) 2.09 GHz	(f_2) 3.74 GHz	(f_3) 5 GHz
Gain (dBi)	Measured with 0.02 FR-4 losses	2.05	2.32	4.47
	Simulated with Lossless material	2.24	3.70	5.53
Efficiency (%)	Measured with 0.02 FR-4 losses	70.12	60.29	66.24
	Simulated with Lossless material	99.8	96.5	99.6



(a) (b)

Fig. 8. The proposed antenna with (a) hand and (b) mobile phone housing and hand.

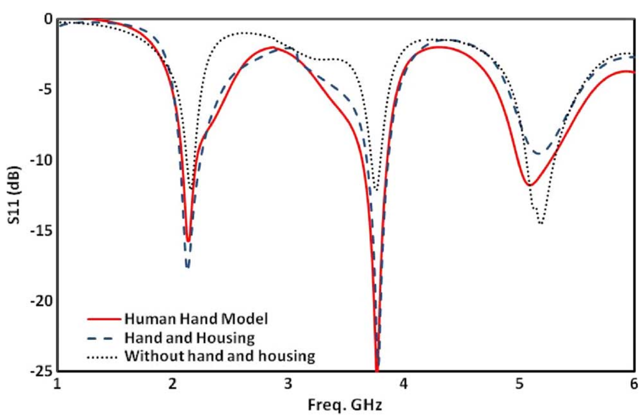


Fig. 9. The effect of the human hand and the plastic housing of the mobile phone on S_{11}.

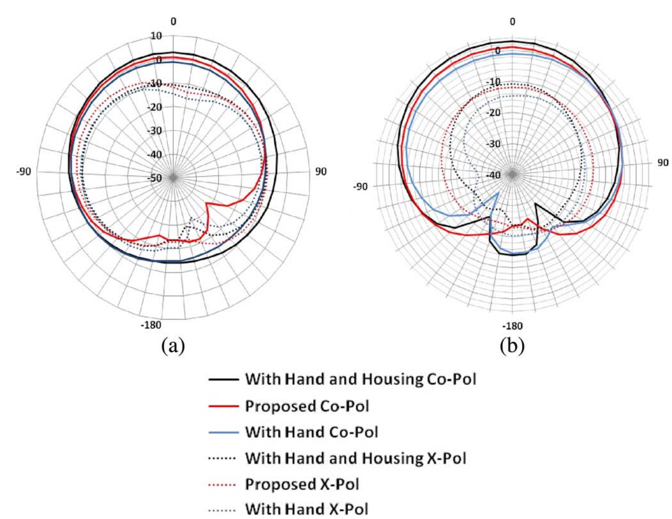


Fig. 10. Normalized Co-Pol and X-Pol radiation patterns at 2.09 GHz band in the presence of human hand model and the mobile phone housing in (a) X-Z plane and (b) Y-Z plane.

2.32 dBi and 4.42 dBi, as shown in Fig. 7. The measured radiation efficiencies for the three bands is 70.12%, 60.29% and 66.24%, respectively, as shown in Fig. 7. These results have taken into account the loss of the FR-4 substrate. If the loss is neglected, the gains and the radiation efficiencies in the three-band are higher, as shown in Table III.

V. EFFECTS OF MOBILE PHONE HOUSING AND USER'S HAND ON ANTENNA'S GROUND PLANE

The effects of a human hand model and a mobile phone housing model on the reflection coefficient S_{11}, radiation patterns, gain and efficiency of the antenna have also been investigated. Fig. 8(a) shows the simulation model of the antenna with the human hand model. The fingers and the palm are attached directly to the ground plane and the main substrate, respectively. When the mobile phone housing model is used as well, the simulation model is shown in Fig. 8(b), where the mobile phone housing model is in direct contact with the

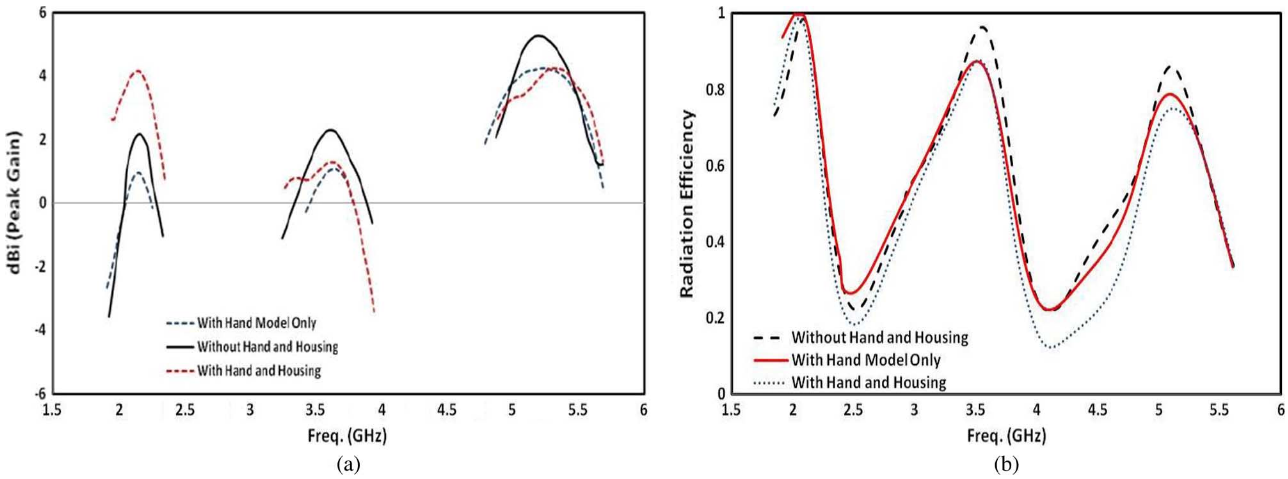


Fig. 11. Results of the proposed antenna with human hand model and mobile phone housing (a) peak gain and (b) radiation efficiency.

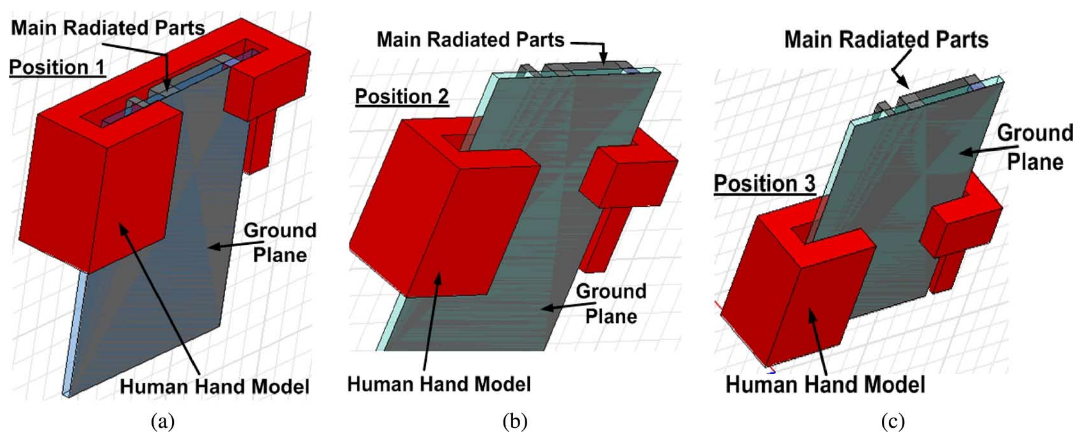


Fig. 12. Simulation model for different positions of user's hand (a) user's hand covering radiator, (b) user's hand partly covering radiator, and (c) user's hand not covering radiator of antenna.

antenna. The relative permittivity and conductivity of 3.5 and 0.02 S/m, respectively, for the mobile phone housing model [33] and of 54 and 1.45 S/m, respectively, for human hand model [34] have been used in simulations. The results in Fig. 9 show that the human hand and mobile phone housing increase the return losses in the two lower frequency bands and slightly increase it in the higher frequency band.

With the human hand and mobile phone housing in place, the radiation patterns at 2 GHz are shown in Fig. 10. It can be seen that the shape of the radiation patterns do not change much. The simulated peak gain and radiation efficiency are shown in Fig. 11. At 2 GHz, Fig. 11(a) shows that the mobile phone housing and the hand increase the peak gain by 2 dB. But if only the human hand is attached directly to the ground plane, the peak gain is decreased by almost 1 dB. This can also be observed in the radiation pattern of Fig. 10 where the antenna loses some energy in the direction of the ground plane and gain from its maximum value. At 3.74 GHz and 5 GHz, the gains drop by approximately 1 dBi, yet maintaining the shape of the radiation patterns. There is no significant change in radiation efficiency when both the human hand model and mobile phone housing are present, as shown in Fig. 11(b).

These results indicate that the ground plane of the proposed design is not too sensitive to the hand and mobile phone housing, thus the antenna has a low ground plane effect.

VI. Effect of User's Hand at Different Positions on Antenna

It is also essential to examine the effects of the hand at different positions on the return loss, gain and efficiency of the antenna. In [35], results of studies showed a dual-band of the antenna was significantly affected by a hand placing on the top of the radiator with 1 cm gap between them. Here, the performances of the antenna with the hand in three different positions, positions 1, 2 and 3, as shown in Fig. 12(a)–(c), respectively, are studied. In position 1, the hand (palm) is placed 1 mm above the top of the radiator and the fingers are touching the ground plane on the other side. The results in Fig. 13(a) show that the first and the third resonances at 2.09 and 5 GHz remain about the same. The second resonance at 3.74 GHz slightly moves to 3.69 GHz. The return losses of the three bands are still greater than 6 dB ($S_{11} < -6$ dB), which is different from the results reported in [35]. In position 2, where the hand is at the centre of the antenna and the palm of the hand partially covering the

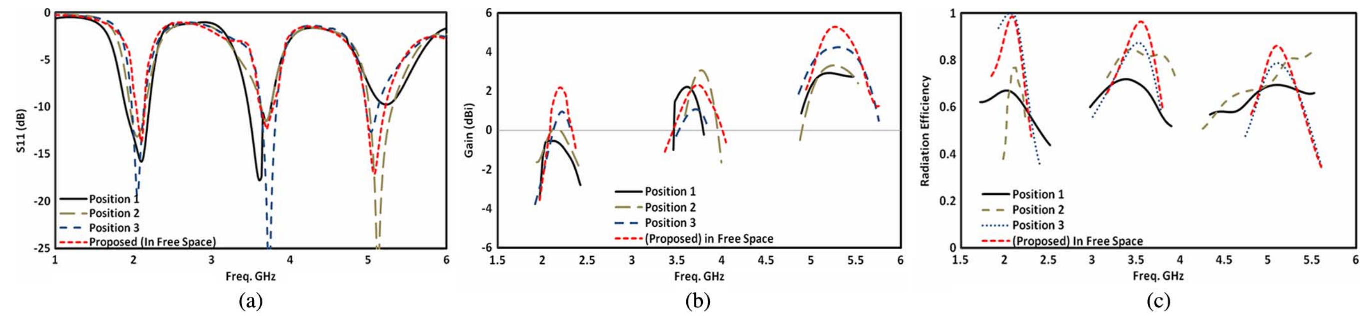


Fig. 13. Effect of different positions of user's hand on (a) the reflection coefficient (S_{11}), (b) gain, (c) radiation efficiency.

radiator with 1 mm gap between them as shown in Fig. 12(b), the results in Fig. 13(a) show that the three resonant frequencies again remain about the same. In position 3, where the hand model is relatively far from the radiator as shown in Fig. 12(c), the three resonances again remain about the same, as indicated in Fig. 13(a).

The simulated results on the gain and radiation efficiency for the three different positions are shown in Fig. 13(b)–(c). It can be seen that, when the hand moves closer to the radiator, the gain drops by almost 0.7 dBi compared with that when the antenna in free space. The radiation efficiency drops to 63% when the hand moves closer to the radiator.

These results indicate that, in these 3 positions, the performance of the antenna is not very much sensitive to the user's hand. The best position, in terms of maximum efficiency and gain, is when the user is holding the mobile phone from the bottom, i.e., position 3. When the user's hand gets closer to the radiator, the gain and the radiation efficiency drop slightly compared with the case when the antenna is in free space. Even for the worst case scenario where the user's hand is completely or partly covering the radiator with 1 mm gap between them, as in positions 1 and 2, the simulation results show that it still can attain above 60% efficiency which is considered quite acceptable for mobile phone applications unlike the design reported in [33] where the radiation efficiency is about 28% at 1795 MHz when the hand is covering the radiator. The gain only drops by 2.2 dBi in the first band of 2.09 GHz and by smaller amounts in the other bands.

VII. Conclusions

The design of a compact multiband PIFA having independent controls of the resonant bands for UMTS, m-WiMAX and 5 GHz WLAN over a wide range have been presented and proposed. The key controlling parameters of the antenna have been studied using the current distributions on the radiator. The antenna has a small size and is thin, making it a good choice for modern mobile phones. Simulation and measurement results have shown good performances in terms of return loss, gain, radiation efficiency and radiation. The ground plane of the antenna has minimal effects on the antenna performance and the performance is not too sensitive to the human hand and the mobile phone housing used in the studies. This feature allows the nearby electronic components to be placed closed to the antenna, making the overall size the mobile phones even more compact and thin.

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